1. BACKGROUND AND OBJECTIVE

The performance of adhesively bonded composite patch repairs is decreased undesirably by thermal residual stresses in the repairs resulting from bonding at elevated temperatures. Since the bonding cycle of the patch repair follows the cure cycle of the adhesive in the repair, it is obvious that the residual stress is reduced by lowering the cure (bonding) -temperature of the adhesive used in the repair. However, lowering the cure-temperature requires a longer curing time to achieve fully developed performance of the repair. Thus, it is highly desirable to develop an efficient bonding process which reduces thermal residual stresses effectively without significantly prolonging the cure time.

In this study, two-step cure-temperature cycles have been developed, which can shorten total cure-time, develop the full performance of the repair, and lower thermal residual stresses. The effect of reduced residual stresses on the fatigue life of cracked aluminum plates repaired with symmetrical composite patches was investigated experimentally and analytically. An analytical model was developed for the design of two-step cure cycles in order to achieve an economical and effective bonding cycle for composite patch repairs.

2. APPROACH

To achieve the research objective, the following tasks have been performed.

- Quantify thermal residual stresses in the repair by introducing effective temperature drop(ΔT_{eff}) in thermoelastic model of the repair.
- Perform parametric study to determine the efficient bonding conditions (bonding temperature and duration) to minimize residual stresses without sacrificing the structural performance of the repair.
- Conduct residual stress experiments on the composite repair and compare with the predictions.
- Develop and experimentally verify a cure kinetic model for the film adhesive (FM73M) used for bonding the composite patch to a cracked aluminum plate.
- Develop a linear viscoelasticity model to predict thermal residual stresses in composite repairs for any multiple step bonding cycles.
- Develop a design diagram based on the model, providing an efficient two-step cure cycle that could reduce thermal residual stresses in composite patch repairs.

The materials used in this study were

Aluminum – 2024-T3
Composite - Graphite/epoxy (IM7/954-2A, AS4/3501-6)
Adhesive – FM73M

3. RESEARCH HIGHLIGHTS

3.1 Quantification of Thermal Residual Stresses by Effective Temperature Drop(ΔT_{eff})

ΔT is defined as the difference of temperature between stress free temperature and servive temperature. Since the curing temperature is generally regarded as the stress free temperature, the residual stress can be estimated with ΔT. Here, 'Effective' means that physical and mechanical properties of the composite and aluminum are assumed to remain constant up to the cure temperature

Directly related to the residual stress in laminates, curvature and residual strain were measured. By thermoelastic laminated plate analysis with the measured curvature and strain, ΔT_{eff} was evaluated.

Table 1. ΔT_{eff} by manufacturer-recommended cure cycle

120 °C Cure	Single-Sided Bonding		Double-Sided Bonding
	Curvature Measurement	Strain Measurement	Strain Measurement
IM7/954-2A	-89 °C	-88 °C	-94 °C
Boron/5521	-89 °C	-87 °C	

3.2 Reduction of Thermal Residual Stresses by Two-step Cure Cycle

Based on glass transition temperature (T_g) and lap-shear strength tests with the adhesive FM73M, it was observed that conventional one-step cure cycles require very long cure time or high cure temperatures. Thus, in order to obtain the desired mechanical properties and T_g at lower cure temperatures, and to shorten cure duration, two-step cure cycles were investigated. This cure procedure involves a lower temperature proceeding a higher temperature. Such a two-step cure cycle ensures low residual stresses and short cure time.

Table 2 lists the measured effective ΔT's for various two-step cure cycles. It is seen that the ΔT_{eff} increases as the cure time of the primary step decreases and the cure temperature of that increases. By considering cure time and ΔT_{eff}, it appears that 82°C/4 hr+104°C/0.5h is the best among the cycles considered and lowers 40% of thermal residual stresses as compared to those of manufacturer-recommended cure cycle.

Table 2. Comparison of ΔT_{eff}'s determined by experiment and model prediction

Two-step cure cycle	ΔT_{eff} by experiment	ΔT_{eff} by prediction
77°C/5hr+121°C/1hr	−65 °C	−67 °C
77°C/5hr+104°C/1hr	−61 °C	−62 °C
82°C/3.5hr+104°C/1hr	−57 °C	−61 °C
82°C/4hr+104°C/0.5hr	−53 °C	−59 °C
82°C/5hr+104°C/1hr	−53 °C	−59 °C
88°C/3.5hr+104°C/1hr	−62 °C	−64 °C
88°C/4hr+104°C/1hr	−62 °C	−64 °C

3.3 Improvement of Fatigue Performance by Reduced Residual Stress in the Repairs

3.3.1 Experimental Observation

The aluminum alloy and the composite used in this work were 2024-T3 and AS4/3501-6, respectively. Pre-cured composite patches were bonded symmetrically to the cracked host aluminum plate. Bonding was done with the adhesive FM73M in an autoclave with the manufacturer-recommended cure cycle and the selected two-step cure cycle (82°C/4 hours+104°C/0.5 hour).

The fatigue test was performed with 6 Hz loading frequency, a positive loading ratio (R_{load}=0.01) was selected in order to avoid buckling. The peak loading stress was 120.5 MPa. The ultrasonic C-scan was conducted to detect and record crack length.

Fatigue lives for repaired and un-repaired specimens are presented in Figure 1. It is seen that the modified two-step cure cycle significantly prolonged the fatigue life of the composite patch repair as compared with that of the recommended cure cycle.

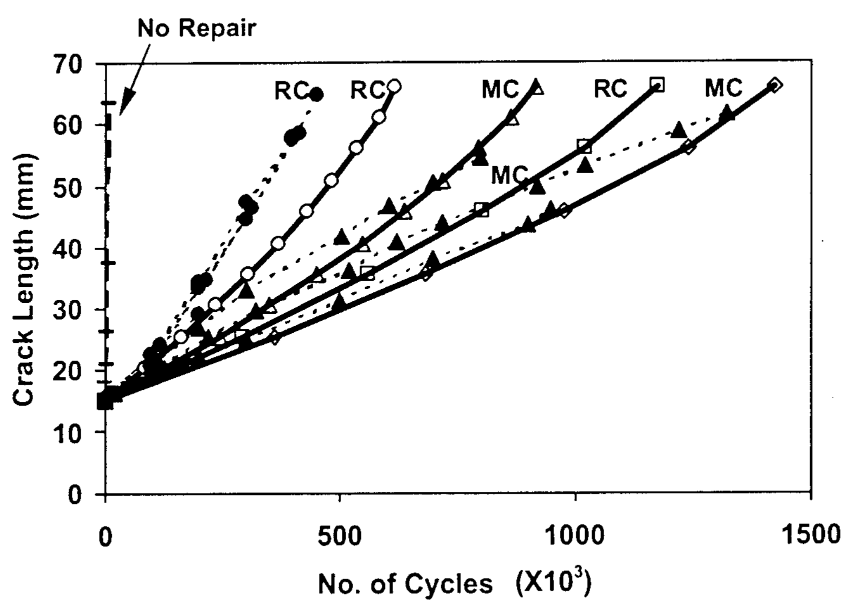

Figure 1. Experimental and numerical results for fatigue crack growth (For recommended cure cycle (RC), experiment : --●--, prediction with strain rate effect :—○— , prediction with linear elasticity : —□— . For modified cycle (MC), experiment : --▲-- , prediction with strain rate effect :—△—, prediction with linear elasticity : —◇— .)

3.3.2 Finite Element Modeling

To predict the fatigue crack growth in the aluminum panel repaired with composite patches, a finite element model was established with the commercial finite element package ABAQUS. In this model, the cracked aluminum plate and composite patches were represented by Mindlin plates. For the adhesive, a layer of 8-node 3D brick

elements was used. In view of the fact that FM73M is highly nonlinear and strain rate dependent, a rate-dependent nonlinear constitutive model for the adhesive was employed. Nonlinear stress-strain curves for the fully cured FM73M for different strain rates were obtained from simple tension tests. For predicting fatigue crack growth, Walker's equation was employed.

The model predictions and experimental results are shown in Figure 1. The prediction obtained based on linear elasticity of the adhesive properties overestimates the fatigue life of the repair. This error is the result of overestimating the load transfer capacity of the adhesive. As shown in Figure 1, the prediction is fairly good if the nonlinear rate dependent behavior of the adhesive is included in the model. On the other hand, although numerical results are not shown, the use of the quasi-static nonlinear stress-strain curve tends to underestimate the fatigue life of the composite patch.

3.4 Cure Kinetic Model of Adhesive FM73M

In order to predict the degree of cure of FM73M at any given time in any given temperature, it is necessary to understand the cure kinetics of the adhesive. A phenomenological model was adopted for the adhesive, FM73M.

Based on the autocatalytic reaction of epoxide and amine groups, one of the most common forms of autocatalytic type kinetic model may be obtained as Equation (1).

$$\frac{da}{dt} = ka^m (1-a)^n \tag{1}$$

where a is the degree of cure, t is time, k is an Arrhenius type reaction rate constant, and m and n are reaction orders. In addition, the cure kinetic parameters k, m and n are the function of temperature. k is given as Equation (2).

$$k = Ae^{(-\frac{\Delta E}{RT})} \tag{2}$$

where A is the pre-exponential constant, R is the universal gas constant, and ΔE is the activation energy.

In order to obtain the cure kinetic parameters, DSC scans were performed with several isothermal temperatures (isothermal scanning) and a programmed temperature (dynamic scanning). From the cure rate histories of the DSC scans, the cure kinetic parameters were determined, and the temperature dependence of the cure kinetic parameters was developed. The modeled cure kinetic parameters are listed in Equations (3a), (3b), and (3c).

$$k = (1.54)e^{-\frac{316.81}{T}} \tag{3a}$$

$$m = (-1.19\times10^{-2})\cdot T + 1.74 \tag{3b}$$

$$n = (4.02\times10^{-7})\cdot T^4 - (1.78\times10^{-4})\cdot T^3 + (2.95\times10^{-2})\cdot T^2 - 2.19\cdot T + 62.66 \tag{3c}$$

where T is temperature (°C). The simulated degree of cure by cure-temperatures are shown in Figure 2 and compared to the degree of cure by experimental data. Solid lines indicate the simulated degree of cure and circles show the experimental results.

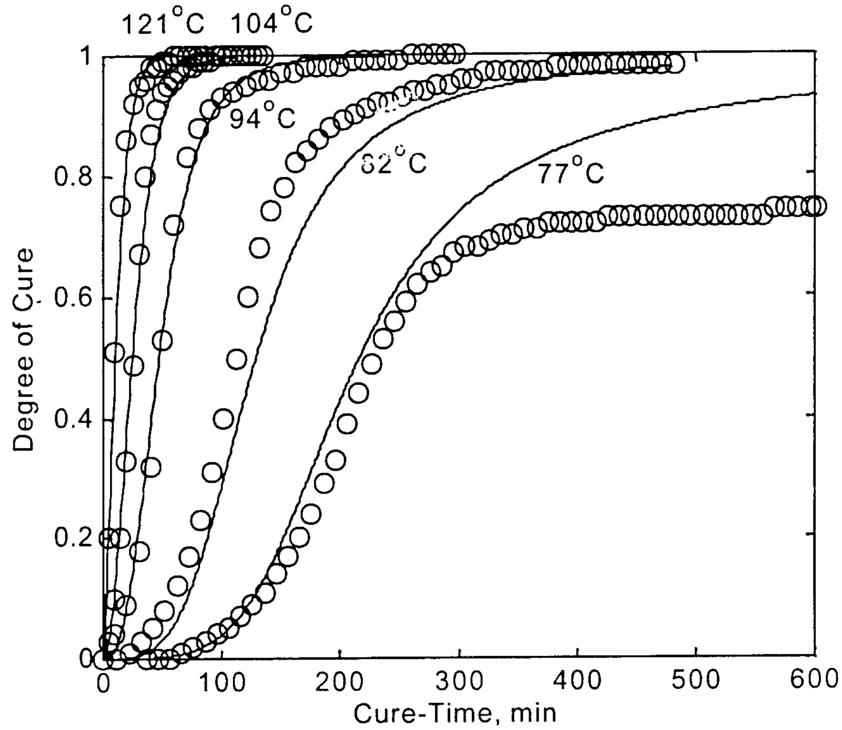

Figure 2. Degree of cure by DSC scanning and model simulation

As seen in Figure 2, the cure kinetic model does not show good agreement with the experimental result for the 77°C cure-temperature, particularly after 5 hours of cure-time. That is because the kinetic model in present work was established based on the vitrification degree of cure near to one, but the experimental result by 77°C cure-temperature shows vitrification-like behavior around degree of cure 0.75. Hence, it is concluded that the cure kinetic model for the cure-temperatures lower than 77°C must be modified.

3.5 Modeling of Two-step Cure Cycles in Composite Patching Repair

The effective temperature drop, ΔT_{eff} was used to provide the experimental correlation with the model prediction. With the thermoelastic analysis, the relationship between thermal residual stresses in the adhesive layer and ΔT_{eff} was established. A linear viscoelasticity model (Maxwell model) was adopted to model the stress relaxation of the adhesive during curing. In addition, material properties of the adhesive were determined as functions of the degree of cure using a number of one-step cure-temperature cycles.

The established model was used to predict ΔT_{eff}'s resulting from two-step cure-temperature cycles. Table 2 lists ΔT_{eff}'s determined empirically and predicted for several two-step cure cycles. It is seen that the predicted ΔT_{eff}'s are in fairly good agreement with the experimentally determined ΔT_{eff}'s.

Based on this model, it was attempted to build a design diagram, as seen Figure 3. The first step cure-temperatures considered were 88°C, 82°C, and 77°C. For the second step cure-temperatures, the temperature of 104°C was taken as an efficient second step cure-temperature in consideration of curing time and lowering thermal residual stresses. Additionally, as seen in Figure 3, the minimum required cure-times at the second step to complete the degree of cure were taken, because longer second step cure-time causes ΔT_{eff} to increase by allowing more stress relaxation in the cure step.

In Figure 3, it is seen that the first step cure has negligible effect on ΔT_{eff} when $a < 0.3$ at the first step cure as compared to the ΔT_{eff} resulting from 104°C one-step cure, which is -76°C. It means that in order to get any benefit of two-step cure cycle, the degree of cure at the first step cure must be at least over than 0.3. In addition, it is clearly seen that as the degree of cure at the first step cure increases, the reduction of ΔT_{eff} also increases.

With this prediction model, it is possible to select other efficient bonding cycles for composite patch repairs.

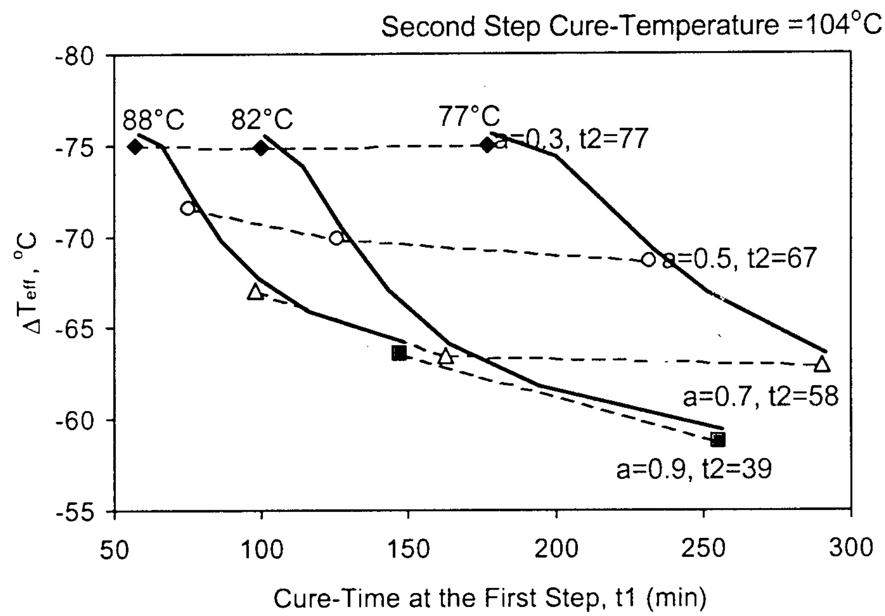

Figure 3. ΔT_{eff}'s for two-step cure cycles with 104°C second step cure-temperature (a : degree of cure after the first step cure, t1 (min) : the cure-time taken at the first step cure, t2 (min) : the minimum required cure-time at the second step with 104°C corresponding to the degree of cure after the first step cure, the temperatures of 88°C, 82°C, and 77°C indicate the cure-temperatures at the first step)

4. PERSONNEL SUPPORTED

- Jeongmin Cho---Graduate student, School of Aeronautics & Astronautics
- Jen Xio---Graduate student, Chemical Engineering

5. PUBLICATIONS

- J. Cho and C. T. Sun, "Lowering Thermal Stresses in Bonded Composite Repairs", Proceedings of the14th Technical Conference, American Society for Composites, September 27-29, 1999, Fairborn, Ohio, pp.894-906.

- Sun, C.T. and J. Cho, "Effect of Lowering Thermal Residual Stresses on Fatigue of Bonded Composite Patch Repairs", Advancing with Composite 2000, May 9-11, 2000, Milano, Italia, pp. 227-232.

- Sun, C.T. and J. Cho, "Optimization of Bonding Cycles to Reduce Thermal Residual Stresses in Adhesively Bonded Composite Patch Repairs", 2000 USAF Structural Integrity Program Conference, December 5-7, 2000, San Antonio, Texas.

- J. Cho and C.T. Sun, "Lowering Thermal Stresses in Composite Patch Repairs in Metallic Aircraft Structure", to be appeared in AIAA.

6. INTERACTIONS/TRANSITIONS

a) Participations/presentations at meetings, conferences, etc-- C. T. Sun and his student have presented papers based on the research results at several conferences as indicated in Item 5.

b) Consultative and advisory functions to DoD labs--Jim Caruthers has had significant interactions with Air Force Materials Laboratory. The cure models being developed here will be part of the next generation high fidelity micromechanics models developed at the AFML.

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14. ABSTRACT
The technology in using composite patches to repair cracked aging aircraft structures has been proven to be efficient and economical. One of the problems resulting from bonding of a composite patch to the metallic host structure is thermal stresses induced from bonding the patch to the host structure at elevated temperatures. The main objective of this research was to develop multi-step curing procedures in order to reduce the level of thermal residual stresses and increase the fatigue life of the composite repair. Several efficient two-step cure temperature cycles have been obtained for the film adhesive FM73. Experiments were performed to verify the significant reduction of thermal stresses resulting from the use of these two-step cure cycles. The effect of reduced thermal stresses on the fatigue life of a cracked aluminum plate repaired with symmetrical composite patches was investigated experimentally and analytically. An analytical model was developed for the optimal design of two-step cure cycles.

15. SUBJECT TERMS
composite patch repair, bonding, cure cycle, thermal residual stress, film adhesive, cure kinetic model, fatigue.

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